DESIGN AND CONSTRUCTION OF A SINGLE-TURN CAVITY-MOUNTED HELICAL ANTENNA

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This work is accepted as fulfilling

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PREFACE

This writer, a submarine communications officer for over five years, has long been frustrated with the state of submarine external communications installations, particularly the antenna arrangements. Thus, with antennae as the field of endeavor, Dalmo-Victor Company in San Carlos, California, producers of eighty-five percent of all air-borne antennae in World War II, was selected as the place of endeavor. Although they were doing no work on submarine antennae, nor were there facilities readily available for initiating a project along those lines, it was felt that practical work on antennae, irrespective of its particular nature, coupled with the exchange of ideas with experienced engineers in the field, would be of considerable benefit.

It is the purpose of this paper, however, to use the experiences and data obtained, during the period January-March, 1955, as a vehicle to depict the problems that industry and junior engineers face in the development of a project, and how they meet these obstacles.

The writer wishes to thank all personnel of the r. f. laboratory of Dalmo-Victor Company for their advice and consideration, and Professor Clarence F. Klamm of the U.S. Naval Postgraduate School for his assistance, encouragement, and cooperation in the preparation of this paper.

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TABLE OF SYMBOLS AND ABBREVIATIONS

(Listed in the order of their use in the text)

C	- Helix Circumference
C_λ	- Helix Circumference in Wave Lengths
AR	- Axial Ratio
n	- Number of Coil Turns
L_λ	- Length of One Turn in Wave Lengths
S	- Spacing between Turns
D	- Diameter of Helix
α	- Pitch Angle
R.F.	- Radio Frequency
VSWR	- Voltage Standing Wave Ratio

CHAPTER I

INTRODUCTION

1. Discussion of Problem

The desirability of flush-mounted antennae on ships and aircraft has long been realized and, accordingly, the properties of various configurations that have suited this prime requisite have been studied in detail. This paper is concerned with one phase of this broad field of endeavor, having as its primary purpose the discussion of the design, development, and testing of a cavity-recessed helical antenna.

2. The General Characteristics of Helical Antennae

The helical antenna, the general form of the antenna of which the linear and the loop antennae are special boundary cases, can be constructed so as to have unique radiation characteristics, with these characteristics being extremely advantageous for specific applications. Basically, the helical antenna, or helix, can, by proper choice and usage of the helix parameters, be made to radiate a nearly circularly polarized electromagnetic wave, in a selected mode of radiation, throughout a pre-determined frequency band. [1] Other general antenna properties (beamwidth and input impedance) are also a function of the helix parameters, with the input impedance also being dependent on the height of the helix above its ground plane.

Fundamentally, the helix will radiate in either the axial mode or the normal mode of radiation, where the former is arbitrarily defined as having the electromagnetic field of radiation be a maximum in the direction of the helix axis, while in the normal mode, the electromagnetic field is a maximum in direction normal to the helix axis. The axial mode, the most practical and efficient manner of helix operation, results when the helix circumference (C) is approximately equal to one free-space wave length of the frequency of operation. This parameter is not too critical in that the axial mode within the range: $3/4 < C_\lambda < 4/3$. This can also be specified as in the region where the mean diameter of the helix coil is between 0.2 and 0.5 wave lengths in size. The only other provision for radiation in the axial mode is that the ground plane be at least 0.5 wave lengths in diameter.

It has been established that a helical antenna radiating in the axial mode will produce a circularly polarized wave, the degree of circularity depending primarily on the number of turns of the coil for antennae of an integral number of one or more turns. This dependency arising from the approximate expression:

$$AR = \frac{2n+1}{n}$$

More exactly, circular polarization is dependent on the condition: $L_\lambda - S_\lambda = 1$ [2]; such precision is behond the

scope of this paper, however. Hence, the first approximation for circular polarization will suffice, and, from which it is evident that the larger n is, the more nearly circular is the polarization. The direction of polarization, whether it is to be right-hand or left-hand, is solely a function of the direction in which the helix is wound.

While circular polarization requires a large value of n, the helical antenna beamwidth requirements are such that a broad-beam antenna requires a small number of turns. This from the fact that the helical antenna beamwidth between half-power points is inversely proportional to the square root of the number of turns. [1] Although the reference develops the expression for beamwidth to be applied to helices having specific design limitations, the general relation holds true for helices falling outside these limits. The conflicting axial ratio and beamwidth requirements necessitate a compromise be the design engineer, this to be discussed in a later section.

The inherent impedance of a helical antenna operating in the axial mode has been found to be relatively constant. [3] It has been empirically developed that the terminal impedance of an axially-fed helix can be approximated by the expression:

$$R = 140\ C_{\lambda}$$

The above holds true for helices for which n 3, and would indicate a serious impedance mismatch (assuming C_{λ} approx-

imately equal to unity) if the antenna were to be fed directly by means of a 50-ohm transmission line. However, it has been found that a short helix can be properly matched to a 50-ohm line by correctly orienting the first 180 space degrees with respect to the associated ground plane. [4] The electrical nature of this transition region, from coaxial cable to antenna, is detailed in the literature. [5] [6]

3. Effect of Cavity-Mounting

Although the electric and magnetic fields for a probe-type cavity mounted antenna have been rigorously analyzed, [7] the analysis of the nature of these fields, and their effect on the polarization of the radiation from a cavity-mounted helical antenna is not so readily obtained. It is sufficient to say that it has been found experimentally that a single turn helical antenna, when mounted in a cavity, exhibits a far greater degree of circular polarization as compared to the same antenna mounted in free space. It has been found, also, experimentally, that, for optimum operation, an empirical relationship exists between the helix diameter and the cavity diameter such that the diameter of the cavity should be approximately 2.2 D. Since the base of the cavity is the helix ground plane, the dimensions are ample for radiation in the axial mode. The depth of the cavity is not critical and can be chosen so as to accomodate a coil with a pitch angle (a) between 12° and 20°.

4. Description of Antenna Assembly

The cavity-mounted helical antenna assembly consists of four basic components:

1. helix coil
2. adapter assembly
3. cavity
4. cavity cover plate.

The helix coil is simple in construction, the final prototype being one and one-half turns of 3/8ths inch tubing with no end-loading of any type. The input, or feed end, is flattened in a plane parallel to the ground plane, this flattened portion being one inch in length; this dimension being the arbitrary choice of the project engineer. This flattened section is drilled to accommodate a screw of the approximate size to fit the adapter (#6-32, in this case). The antenna may then be tuned by screwing the screw further into the adapter or moving it out, thus repositioning the first quarter turn of the helix closer to or further away from its ground plane.

The adapter assembly, a modified standard UG-921/U RF connector, provides a means of physically securing the coaxial feed line to the antenna assembly, and acts as a lossless electrical connector between the coaxial line and the antenna. Its details are unimportant and will not be discussed any further.

The cavity cover plate, a low RF loss dielectric piece, functions electrically to improve both the axial ratio and the voltage standing wave ratio; the plate acts physcially to hermetically seal the antenna, thus presenting a zero-drag surface and also as an upper support for the coil. The top section of the coil is either glued onto the cover plate, or secured by means of a screw; the former method is preferable.

CHAPTER II

ANTENNA DESIGN AND CONSTRUCTION

1. Electrical Specifications.

For every electronic device, irrespective of its nature, there are contractor's specifications that must be met. This helical antenna assembly was no exception, its electrical specifications being as listed below:

1. Voltage Standing Wave Ratio.........1.5:1 or less across the band
2. Voltage Axial Ratio.................3.5:1 or less across the band
3. Half power beamwidth................50° or greater across the band.

The reasoning behind the above specifications is discussed in the appendix. The band, in this instance, is the frequency band 565 - 975 megacycles per second inclusive.

To insure that this type antenna could readily be produced in quantity with a minimum of individual tuning and adjusting, the prototype antenna must fall well within the specifications listed above. "Well within" is defined in this case, as a VSWR of 1.3:1 maximum and a VAR of 2.8:1 maximum. The amount of time and effort a project engineer will spend in bringing a prototype model out of the shadow zone, below the contractor's limits, but above the company's limits, is governed primarily by the project engineer's estimate of the situation, and secondarily by the company's deadline date for delivery of the preproduction model(s).

2. Design Considerations and Criteria.

The writer then, in his capacity as project engineer, was given the design specifications, and an aluminum cavity measuring 13 1/8 inches I.D. by 4 1/2 inches in depth, and was advised by the Director of Research at Dalmo-Victor merely to build a helical antenna to meet the requirements. Manufacturing considerations were such that it was extremely desirable to use the already-made cavity; thus, this became a non-variable.

The immediate questions to be answered by the engineer in the development of this antenna were:

1. What diameter coil was most suitable?
2. How many turns were needed?
3. What size wire should be used?
4. Would top-loading of the coil be necessary?
5. What type dielectric should be used for the cover?
6. What thickness cover would be most suitable?

The antenna was to be off-center fed; that is, the feed point was located on the helix perimeter rather than symmetrically at the helix center. This method of feeding eliminated a linear element (otherwise necessary to get from the feed point to the helix perimeter) which, previous tests had shown, acted to the detriment of the circular polarization characteristics.

General or approximate answers to some of the above

questions were to be found in the literature. Partial answers to others were provided by other engineers who had devoted time to helical antennae projects. Thus, this project consisted essentially of mechanically building the form and winding the coil, and electrically combining these initially-proposed answers with modifications gained by experience, the result to be a produceable prototype.

It was decided by this writer that he would commence the project using 0.25 inch diameter annealled copper tubing as the antenna wire. The helix coil would be wound on a 5.25 inch form, and the antenna coil would be one and one-half physical turns in length. These decisions were all based on the advice of contemporaries, and, in general, are to be verified in the writings of such acknowledged experts in the field as Kraus and Kandoian. It was further decided that initially the antenna would not have top loading of any sort if possible. Top-loading was advantageous in tuning the antenna VSWR-wise, but it had been found experimentally to adversely affect the voltage axial ratio characteristics. Figure 3 illustrates the differences in VSWR resulting from the presence or absence of standard top loading. Standard top-loading consisted of three turns of flattened tubing formed around a solid polystyrene cylinder 5/8 inches in diameter as shown in Figure 4.

2. Helix Construction.

The form for shaping the coil was a hollow metal cylinder

5.25 inches in diameter, around which had been firmly secured cross-section paper --- this for accurately sketching the configuration of the helix before it was wound, and also for ascertaining and recording any changes in the shape of the coil after the antenna had been properly tuned. Into the hollow form was inserted a support similar to that proposed as the center support of the coil in the complete helical antenna assembly (if it was later decided to use the cover plate only as a means of support, this insert would have acted solely as an aid in winding the coil). Further form details are unimportant.

The feed end of the helix was constructed by bending the lower (assuming the helix position to be vertical) end of the coil 90° downward in a direction parallel to the helix axis, filling the bent segment (a 3/4 inch vertical element) with silver solder, drilling and tapping along the length of this segment for the proper size headless screw (# 6-32 in this case) which was to fit into the coaxial adapter. This work was to be accomplished by the project engineer, and illustrates the fact that, in most of the smaller electronics industries, project engineers are expected to be mechanically proficient as well as being professionally literate. This method of fabricating the feed end was used only on this size wire. The ultimate prototype, using 3/8ths inch tubing, had the feed end fashioned in the manner described in Chapter I.

CHAPTER III

EVALUATION OF ANTENNA VARIABLES AND THEIR EFFECTS

1. Testing and Adjusting Helix.

The major step in the development of this project was the testing of the prototype antenna. It was in this phase of the project that the questions stated earlier were to be answered, and the original values of the antenna parameters were to be evaluated and modified as necessary. There were three series of tests to be run on this antenna:

1. Testing and tuning for proper VSWR across the band.
2. Adjusting for proper VAR across the band.
3. Measuring beamwidth across the band.

The last listed series of tests were considered to be relatively minor. Beamwidth between half-power points, as brought out in Kraus [1], is primarily a function of the number of turns; hence, a helix of approximately one and one-half turns will normally have a beamwidth on the order of 55°. Difficulties in meeting the beamwidth standards were invariably mechanical in nature.

Hence the question became, "Which of the first two type tests was better suited for evaluating and adjusting the helix variables?". Since axial ratio is also a function almost solely of the number of turns, and more subtly, dependent on the relation between the length of a turn and the turn spacing, it appeared practical to adjust the majority of helix parameters

on the basis of VSWR values. The laboratory set-up, then, for measuring standing wave ratios was as shown in Figure 2.

The laboratory technique used was to introduce a slotted line between the unknown impedance (the antenna assembly) and a pulse modulated signal source. The variation in r.f. voltage along the longitudinal slot was determined by means of an exploratory probe, containing a crystal detector, connected to a calibrated amplifier. The VSWR could be read directly from the amplifier. Fundamentally, this procedure is the first step in the standard technique for determining the impedance of an antenna. Actual impedance values would have no practical value, however, since the prime concern is regarding the amount of power that will be reflected, and thus, lost. The normal precautions, as detailed in such texts as Silver [8], were recognized and followed. Probe penetration into the slotted line was kept at a minimum to reduce the shunt conductance and eliminate field distortion insofar as possible. A reflection-free area was used for obtaining measurements, and appropriate connectors were used to match the various units.

Tuning the antenna so that it met the VSWR specifications was extremely tedious and required the utmost care. As has been mentioned previously, the basic tuning method was the variation in the ground plane to coil spacing; the effects of other parameters on the tuning is discussed in detail in the next section. The nature of the effects of the variation in spacing of the transition section [5] (the first quarter

turn) are illustrated in Figure 3. Obviously, it was necessary to obtain optimum spacing for proper evaluation of the other helix parameters. Experimental developments resulted in shaping the coil in a manner such that the first quarter turn had a much smaller pitch angle than the helix proper (the remaining one and one-quarter turns). The methods employed in determining the optimum configuration and spacing of the transition section were the aforementioned screw adjustment technique plus the use of metal and dielectric plates inserted between the ground plane and a selected segment of the transition section. The use of the plates gave an indication as to the optimum spacing of the particular segment being analyzed. The prime criterion for decision was, of course, a minimum mean VSWR across the frequency band.

Axial ratio adjustments were not nearly so critical, being as theory implies, primarily a function of the number of turns, turn length, and turn spacing. Thus, a coil has a basic characteristic degree of circularity that, for this type assembly, could be varied only slightly manually by adjusting the regularity of the coil itself, and the symmetry of orientation of the coil with respect to the cavity. Interestingly, the voltage axial ratio was affected to a great extent by the thickness of the dielectric cover as illustrated in Figure 4, and to a lesser degree by the type dielectric material used as a cover plate. The electromagnetic action associated with these effects is beyond the scope of this paper; however, the

experimentally observed consequences of these parameters are discussed in the next section.

2. Effect of Helix Parameters

Conductor Diameter --- The coils for the first models of this antenna were constructed of one-quarter inch diameter copper tubing. This selected value was based on prior successful endeavors with this type problem [4]. This sized d made for a tunable antenna VSWR-wise, although the tuning was extremely critical. Also, the AR was inherently poor. In spite of the fact that Tice and Kraus [9] have stated that d has no effect on the terminal impedance of a helix, it is inferred that this neglects the effect of the ground plane. Further, Kandoian [10] implies that d should be on the order of 1/15 of the mean coil diameter for this type assembly. These considerations resulted in the decision to use 3/8ths inch copper tubing. The ease with which this type antenna could be wound led to its use in the final prototype. Comparison between antennae of one-quarter inch tubing and 3/8ths inch tubing is illustrated in Figure 6.

Helix Diameter --- This parameter was not too critical in that experimental results indicated that D could be varied as much as eight per cent on either side of the ultimate value, 6.25 inches, with no appreciable effect on either the VSWR or the VAR.

Coil Length --- This parameter followed theory [1] in that turns in excess of one and one-half narrowed the beamwidth below design specifications. At the other extreme, a coil length of less than one and one-third turns was unusable from a VSWR standpoint, as shown in Figure 7. The degree of circularity was enhanced by the use of as large a number of turns as possible. Consequently, the final prototype employed one and one-half turns.

Top(End)-Loading --- Various configurations of end-loading were evaluated; the net effect being that top-loading increased the ease with which a coil could be tuned (hence, reduced the criticalness of the ground to coil spacing of the transition section), but the top-loading had a deleterious effect on the VAR to such a degree that it was decided not to use any loading.

Cover Plate Effect --- All types of covers tested aided somewhat in reducing the mean VSWR across the frequency band. The differences between types were so small in this phase of the testing though, that the choice of type cover was entirely dependent on its effect on the VAR. Figure 8 illustrates the differences produced by covers of different type dielectric materials. Experimental results indicated that a thickness of one-quarter inch resulted in the optimum Var in this frequency band. Cover thickness had a definite effect on the VAR and a negligible effect on the VSWR.

3. Test Results and Conclusions.

Based on the above detailed experimental results, a helical antenna assembly using a coil made of 3/8ths inch annealled copper tubing, having a coil length of one and one-half turns, and a mean diameter of 6.25 inches is best suited for operation in the frequency band 565 - 975 megacycles per second. The coil should have no top-loading, and should be located on the coil perimeter rather than symmetrically located coincident with the helix axis. The cover plate should be made of 1/4 inch dielectric material similiar electrically to the commercial E-poxy.

It can be further concluded that, in general, a helix of a small number of turns can, in the proper enviornmental conditions, exhibit very closely the characteristics of the more complete type of helix as discussed in Kraus [1]. Further, when deviating from the standard limits,
no parameter can be assumed; all must be investigated.

CHAPTER IV

TEST EQUIPMENT AND TECHNIQUES

1. VSWR Equipment and Techniques.

The voltage standing wave ratio testing arrangement was outlined in Chapter III. The specific equipments used in these tests were:

1. Hewlett-Packard Model 415A Square Law Detector
2. Hewlett-Packard Model 610B Signal Generator
3. Hewlett-Packard Model 805A Coaxial Slotted Line.

As the probe penetration was at a minimum, no corrections were made for the effect of the probe shunt conductance.

2. VAR Equipment and Techniques.

The basic test bench for radiation measurements consisted of a horizontal, 5 foot diameter, circular ground plane with provisions for flush-mounting the test antenna assembly at the center. A balanced coaxial receiving dipole assembly, supported above the ground plane on a 5 to 8 foot radius (radius varied by repositioning a movable support) from the center, is mounted on a wooden boom which can be rotated about its own axis in the vertical plane. A motor is provided to turn the dipole in the horizontal plane (the dipole is horizontally polarized). The dipole is removable to facilitate the use of different dipoles at different frequency bands.

Power received by the particular dipole in use is detected by a IN23B crystal at a level insuring operation as a square law detector, and passed through a rotary transformer to an amplifier. The amplifier drives the pens of a modified RD-47A two-pen recorder. A wooden boom supporting the dipole is pivoted on an axis through the center of the ground plane and can carry the dipole through 190° of arc over the center of the ground plane. The boom can be driven either manually or by a motor. A selsyn transmitter is geared to the RD-47A recorder to provide paper motion for the desired calibration of ten degrees per division on Esterline-Angus paper.

The pattern receiver is a linear amplifier, and drives one pen of the recorder to indicate relative power. As the dipole rotates through the planes of the major axis and minor axis of the voltage polarization ellipse of the test antenna, a maximum and minimum response is recorded. While the support carrying the dipole travels through 190°, a complete record of maximum and minimum voltages detected is traced on the recorder paper. The envelope of maximum response is the power pattern in the plane of the major axis of the polarization ellipse, and the envelope of minimum response is the power pattern in plane of the minor axis of the polarization ellipse. The excursion from maximum to minimum defines the power axial ratio, readily converted to voltage axial ratio, and is recorded for all points in the plane examined. This arrangement is primar-

ily for obtaining the required beamwidth information. VAR data is obtained with the dipole rotating in the horizontal plane in a fixed position above the test antenna. A Model 415A detector is used to read VAR directly, eliminating the need for converting power db reading to voltage values.

Reflections from other surfaces in the area were such as to render the pattern table unusable at these frequencies. The entire arrangement had to be relocated in a reflection-free area and, since the boom could not be moved, no beamwidth data was obtainable for this antenna. The required VAR data did not necessitate the use of the boom, but only a mounting for the dipole assembly and its driving motor.

BIBLIOGRAPHY

1. Kraus, J. D. — ANTENNAS, McGraw-Hill Electrical and Electronic Engineering Series pp 173-216

2. Kraus, J. D. — THE HELICAL ANTENNA, Proc. I.R.E., Vol. 37, pp 263-272, March 1949

3. Glasser, O. J. and Kraus, J. D. — MEASURED IMPEDANCES OF HELICAL BEAM ANTENNAS, Journal of Applied Physics, Vol. 19, pp 193 - 197, February 1948

4. Will, K. E. — DEVELOPMENT AND ACCEPTANCE OF ANTENNA AT-230 (XA)/APT AND ANTENNA AT-230/APT Wright Air Development Center Technical Report No. 52-159, June 1952

5. Radio Research Laboratory Staff — VERY HIGH FREQUENCY TECHNIQUES Vol. 1, 1st Edition, McGraw-Hill, 1947

6. University of California Staff — IMPEDANCE OF ANTENNAS WITH INPUT CONFIGURATIONS, Report No. 157 August 22, 1949

7. University of California Staff — ELECTRICALLY SMALL CAVITY ANTENNAS Report No. 143, August 17, 1948

8. Silvers, Samuel — MICROWAVE ANTENNA THEORY AND DESIGN M.I.T. Radiation Laboratory Series No. 12

9. Tice, T. E. and Kraus, J. D. — THE INFLUENCE OF CONDUCTOR SIZE ON THE PROPERTIES OF HELICAL BEAM ANTENNAS Proc. I.R.E., Vol. 37, p. 1296 November 1949

10. Kandoian, A.G. — WIDE FREQUENCY-RANGE TUNED HELICAL ANTENNAS AND CIRCUITS Federal Telecommunication Laboratories, Inc., Nutley, N. J.

11. Spangenburg, K. R. — VACUUM TUBES McGraw-Hill Electrical and Electronic Engineering Series, pp. 670-674

APPENDIX I

ANTENNA SPECIFICATIONS, THEIR BACKGROUND AND DETERMINATION

The limiting value of the voltage standing wave ratio was based primarily on the characteristic behaviour of magnetrons; when confronted with a varying load, these tubes tend to mode-jump. This action is explained in detail in such texts as Spangenburg [11]. Although it is desirable to have the VSWR as low as possible, consideration must be given to industry and the problems of mass-producing antennae having specified electrical limitations.

The VAR requirements were established, based on the fact that 3.0 db represents the half power point in determining antenna beamwidth and polarization characteristics. Hence, 3.5 db was again a compromise value involving considerations of production and electrical characteristics.

The beamwidth criteria were military decisions based on what was obtainable within space and weight limitations as compared with what would be usable from a tactical viewpoint.

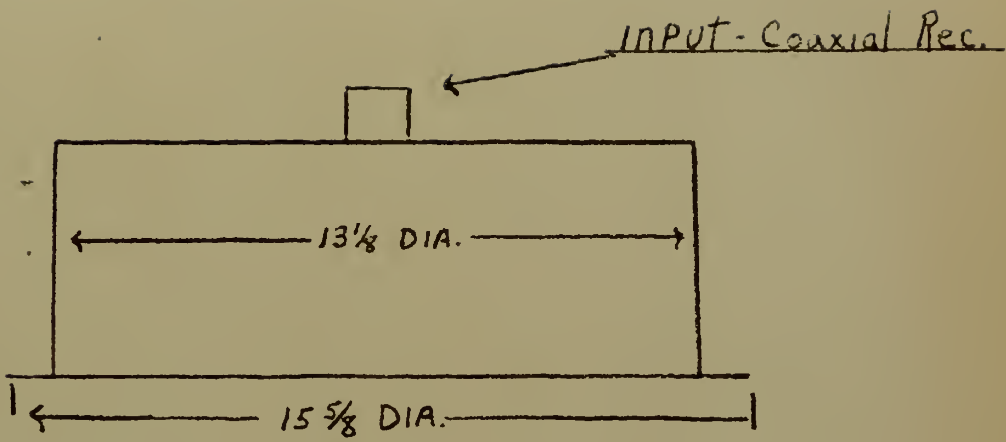

FIGURE 1 ANTENNA ASSEMBLY MOUNTING CAVITY

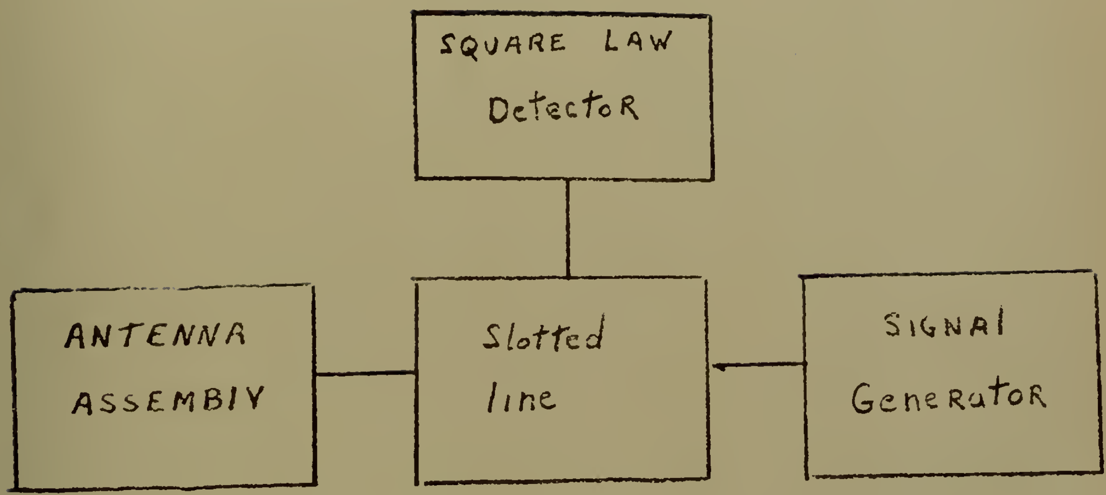

FIGURE 2 VSWR TEST ARRANGEMENT

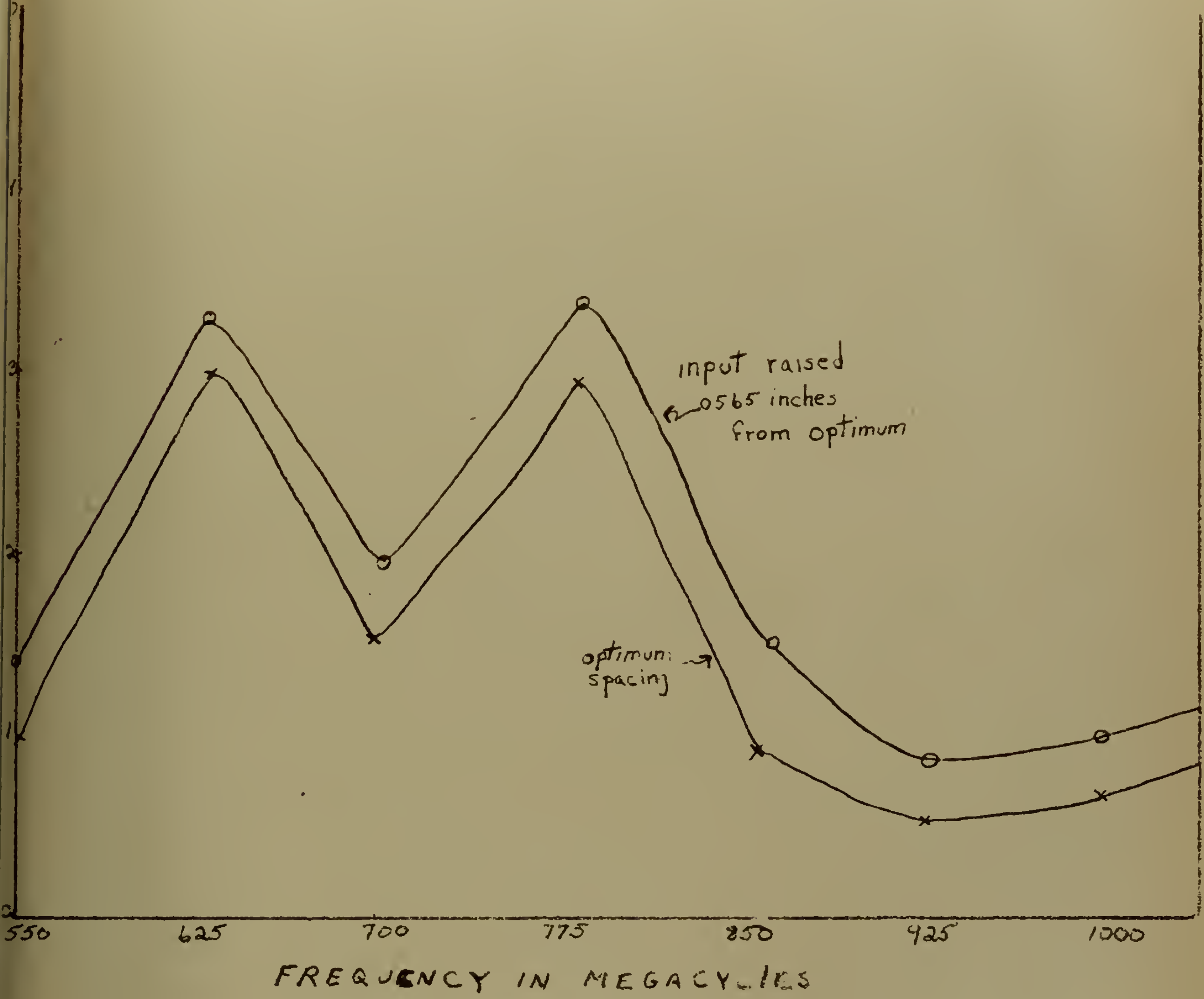

FIGURE 3 EFFECT OF VARIATION IN SPACING ON VSWR

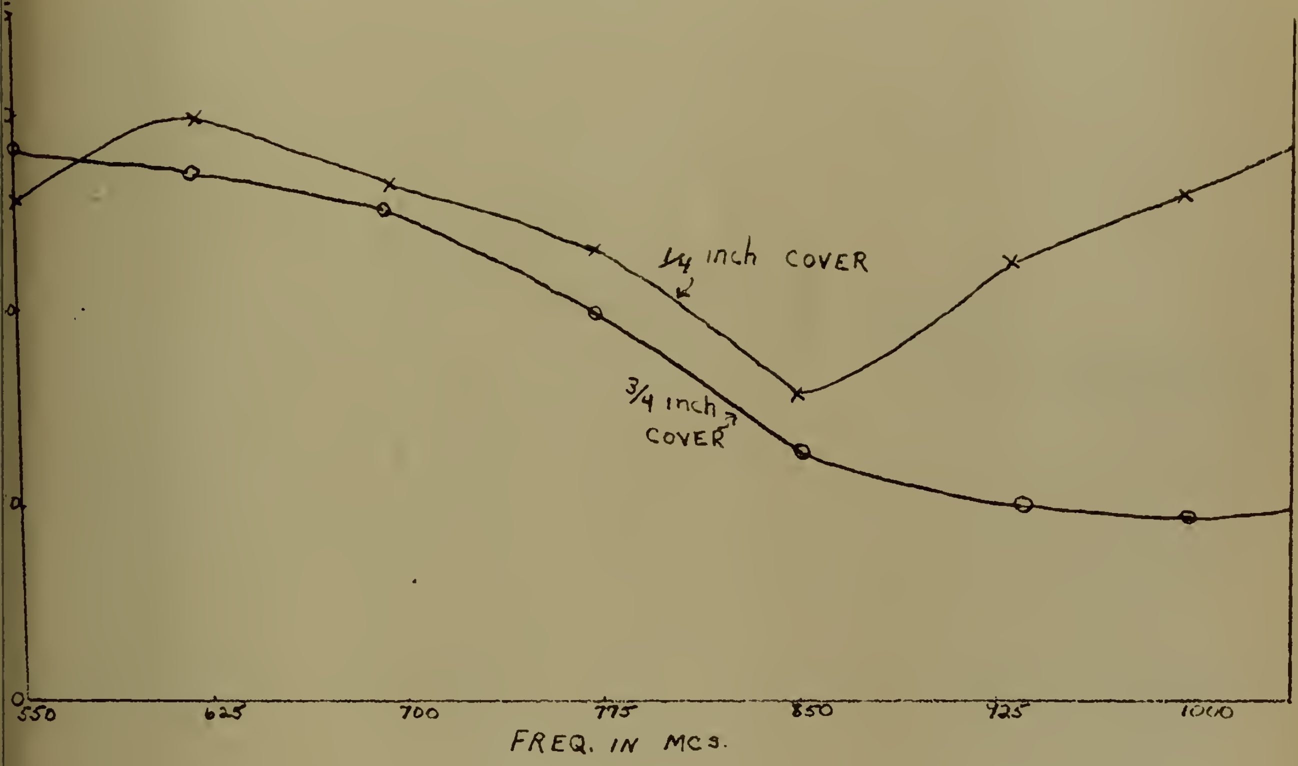

FIGURE 4 EFFECT ON VAR OF COVER THICKNESS

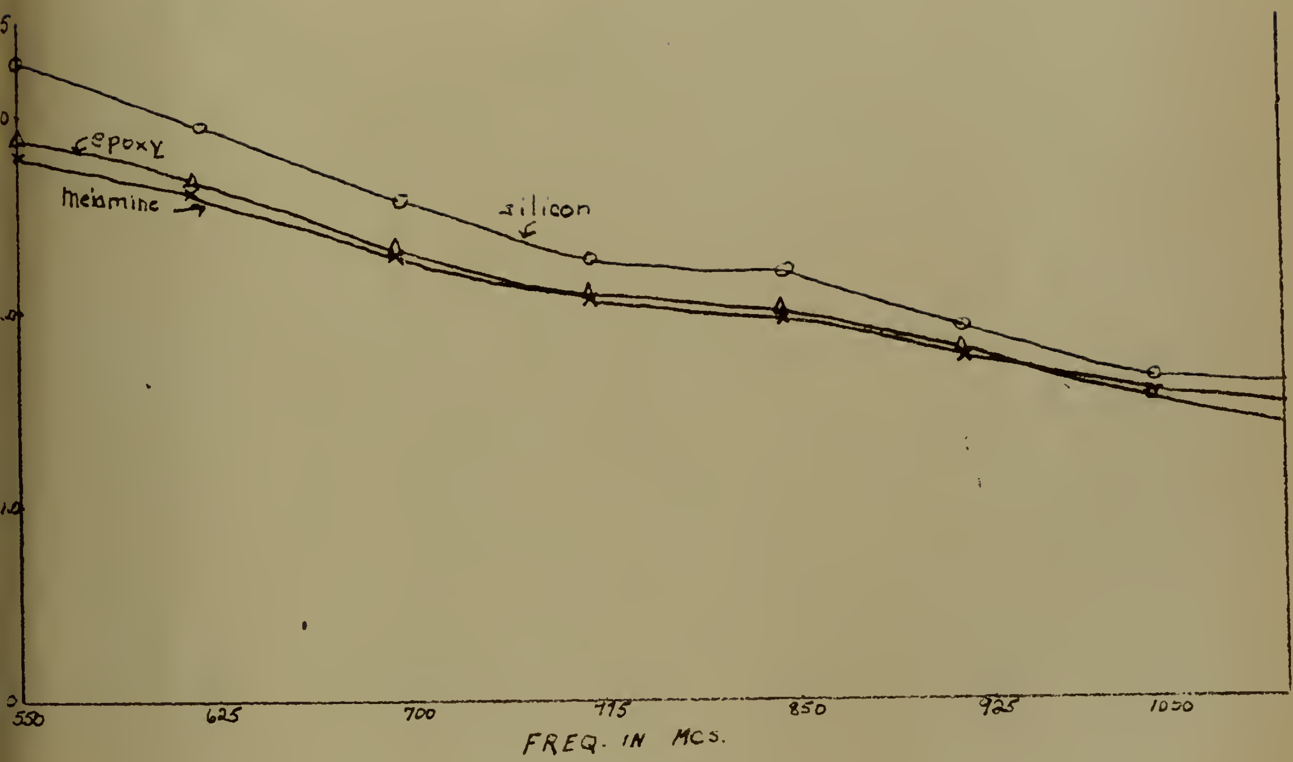

FIGURE 5 EFFECT ON VAR OF COVER MATERIAL

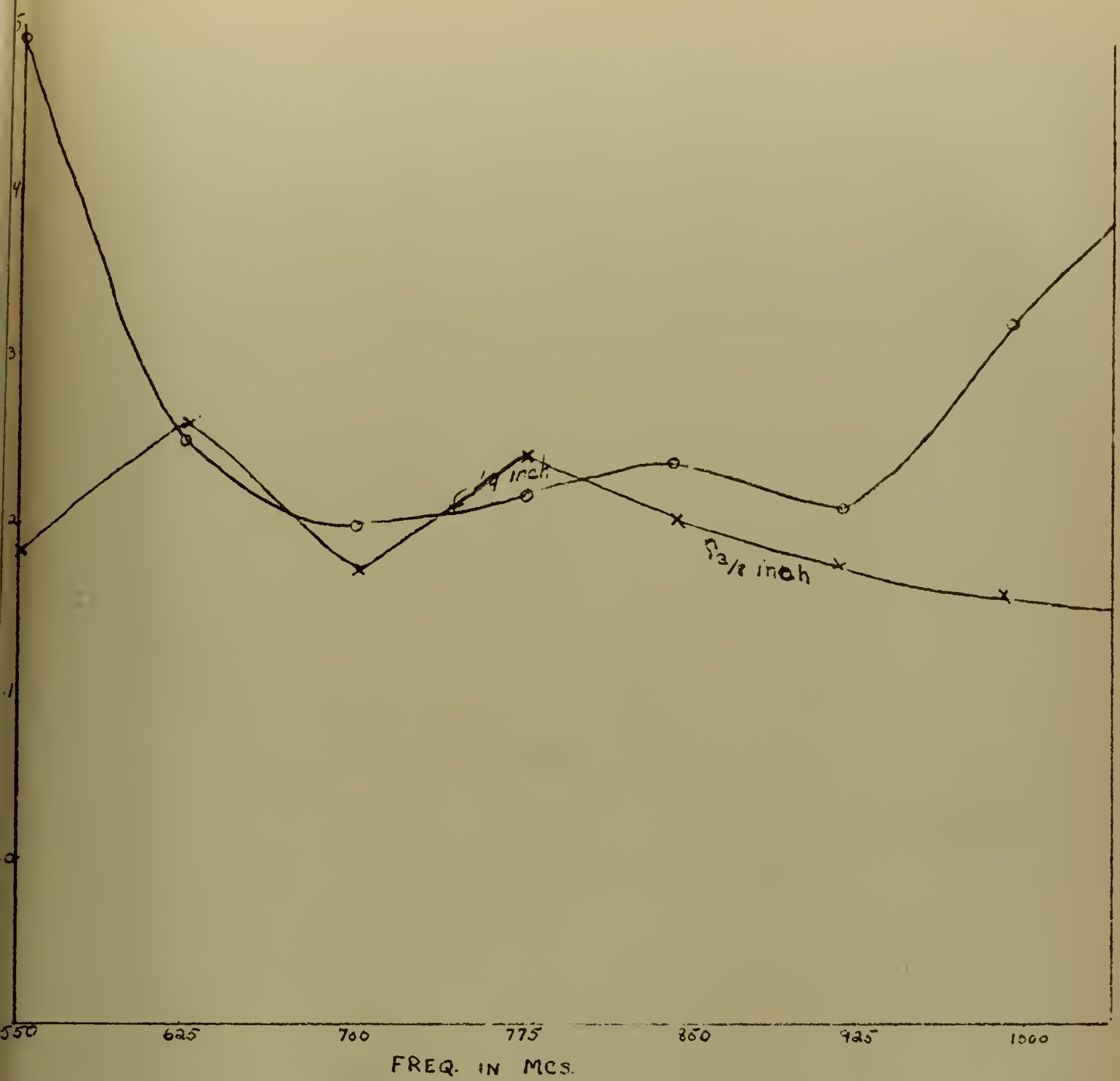

FIGURE 6 EFFECT OF d ON VSWR

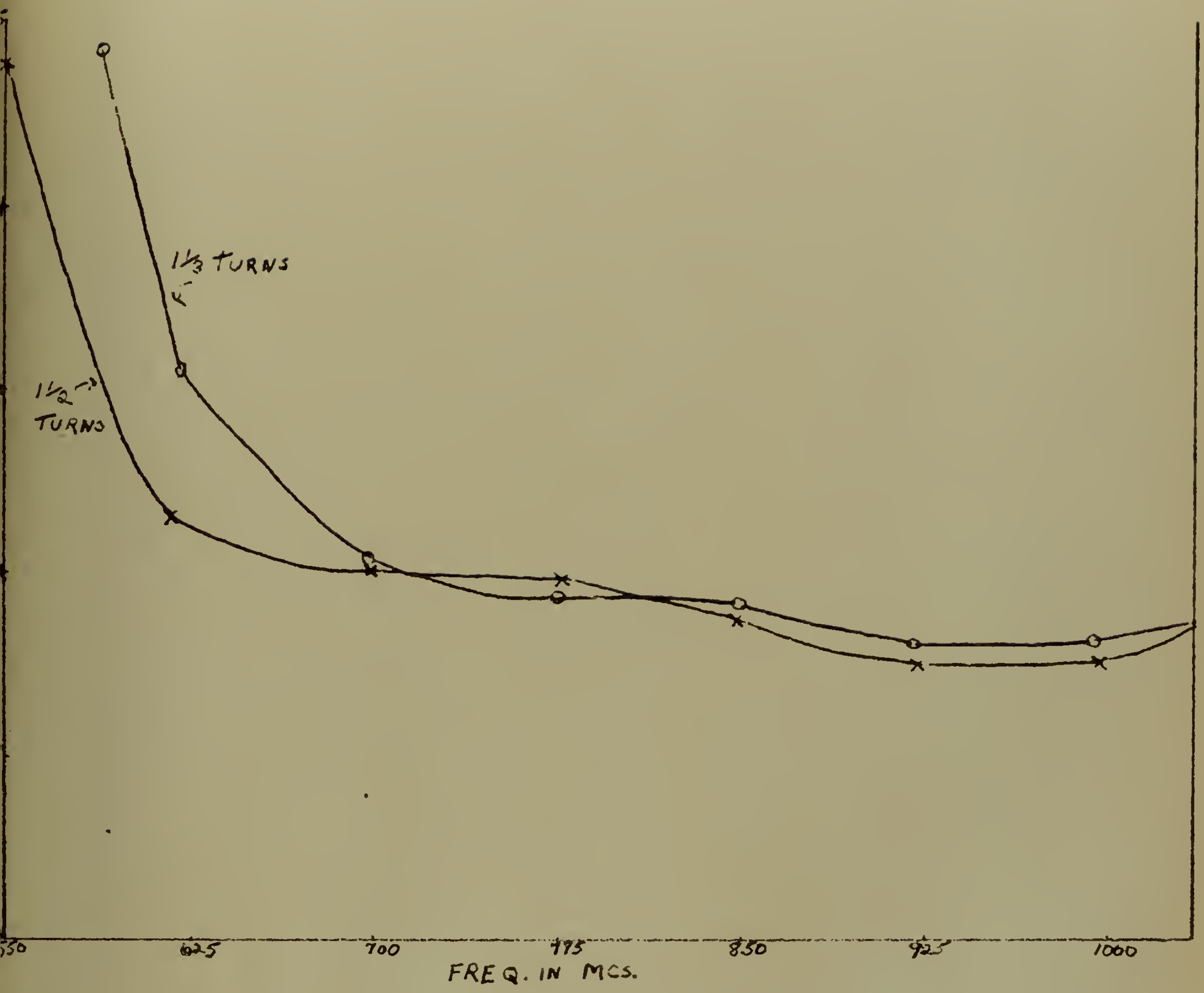

FIGURE 7 FFFECT OF n ON VSWR

Thesis 28475
T77 Treacy
Design and construction of a single-turn cavity-mcunted helical antenna.